A

FAN AND VENTILATION DUCT NOISE IN SUBMARINES

S.J. CLAMPTON
NAVED (Noise & Vibration Engineering Department) VSEL, UK

ABSTRACT
Fans and their associated ventilation ducts are amongst the major sources of airborne noise encountered within a submarine. Health & Safety Standards require that the ship's crew are not exposed to unnecessary high levels of noise and have a suitable environment free from intrusive noise in order to work and rest. The problem with noise emitted from fans and ducts in submarines can be categorised as follows:

a) In machinery spaces where there is a significant population of fans, for recirculation and cooling purposes, their combined contribution is significant compared with the total airborne noise level due to all machinery sources in such compartments.
b) Noise can be transmitted via supply and exhaust ventilation ducts from noisy fan plenums to quiet compartments elsewhere in the boat.
c) Due to necessary space constraints within a submarine, a fan plenum can be situated adjacent to a quiet compartment, and hence airborne noise transmitted via common structural boundaries then becomes significant.

Using selected case studies this paper shows how one can determine the airborne noise contribution of fans and ventilation ducts in submarines, and the appropriate acoustic treatments that may be necessary, through the use of computer-based predictive models.

RESUME
Les ventilateurs et leurs conduits de ventilation associés sont entre autres les principales sources du bruit aérien rencontrées dans un sous-marin. Les normes qui régissent la santé et la sécurité exigent que l'équipage de bord ne soit pas exposé aux niveaux élevés du bruit superflus et qu'il ait un environ approprié à l'abri du bruit importun pour travailler et reposer. Les problèmes associés au bruit émis par des ventilateurs et des conduits dans les sout-marins se catégorisent comme suit:

a) Dans les locaux des machines où il se trouve un nombre important de ventilateurs aux fins de recirculation et refroidissement, leur contribution combinée est important en comparaison du niveau de bruit aérien global en provenance de toutes les machines dans de tels compartiments.
b) Le bruit peut être transmis par les conduits de ventilation d'alimentation et d'échappement à partir des plénums de ventilateurs bruyants vers des compartiments silencieux autre part du bâtiment.
c) A cause des contraintes nécessaires en ce qui concerne l'espace dans un sous-marine, un plénum de ventilateur peut être situé contigu à un compartiment à faible niveau de bruit et ainsi le bruit aérien transmis pas les structures limites communes devient alors important.

Par l'emploi des cas practiques sélectionnés, ce traité démontre comment l'on peut déterminer la contribution du bruit aérien et des conduits de ventilation dans les sous-marins, ainsi que les traitements acoustiques appropriés qui peuvent éventuellement être nécessaires, par l'intermédiare des modèles à prédiction automatisés.

1- INTRODUCTION

If asked to make a link between noise and submarines, most people would think of surface vessels using sonar to detect a submarine's radiated or reflected noise signature. This aspect of noise has been made popular through the public media on naval warfare. A lesser known, but still an important aspect of noise from the point of view of the submarine crew is airborne noise within the submarine itself. From a health and safety point of view, levels of airborne noise and its control are important for three main reasons:

a) In machinery areas, the crew must be protected from high levels of noise in order that their hearing is not impaired or damaged.
b) In areas of the boat such as the Control Room, Wireless Room and other offices, noise must not inhibit clear audible communication.
c) In compartments such as cabins or the Sick Bay, noise must not disturb the crew's rest and sleep.

The number and type of airborne noise sources within a submarine are many and varied and because a submarine is an enclosed system, it is not surprising that fans are amongst the major sources of airborne noise. Wherever air needs to be supplied and re-circulated in the boat, there will always be a contribution due to fan noise in one form or another.

This paper discusses how one can predict levels due to fan noise in a submarine and identify the methods required to reduce its contribution to within acceptable limits, through the use of computer-based acoustic models.

2- COMPUTER MODELS

From past experience it has been found that if potential airborne noise problems are identified before the construction of a submarine takes place, then the necessary acoustic treatments to reduce noise levels can be incorporated in the initial design of the boat. This saves much time and effort during the submarine build and avoids possible costly retrofits once construction has been completed. Predictive work can, of course, be also used to identify the required treatments to ease noise problems which already exist in submarines in service.

The advent of more stringent legislation, which limits the amount of noise that personnel can be exposed to on health and safety grounds, and the requirement for faster and more sophisticated methods of acoustic predictions, has given greater impetus to the use of computer generated acoustic models. Models generated by computer offer the following advantages:

a) Data can be processed much more quickly, efficiently and accurately than by performing calculations by hand.
b) Alterations due to changes in compartment size or structure, positioning of machines and other noise sources, flow rates in ventilation ducts, etc., can be readily incorporated without the need for a full re-calculation.
c) Access to database information for example on acoustic absorption coefficients, transmission losses and machinery source levels, is readily available and can easily be transferred into the relevant acoustic model.

3- ACOUSTIC MODELS

3.1 Acoustic elements

All acoustic models are composed of three basic components: noise sources, receiver points, and acoustic transmission paths linking sources to each receiver point.

3.2 Sources

The first stage in creating any acoustic model is the determination of the sound power levels (SWLs) of each noise source. For the majority of airborne noise investigations in submarines, octave or third-octave analyses are used. For fans, methods of obtaining their SWLs over such bands are well documented, as indicated below. Once the source SWLs have been entered in a computer acoustic model they can be amended with ease as more up-to-date information becomes available, as would be the case at the following stages in a boat build:

a) Design stage. Usually at this point only the required duties of the fans have been established but not their type or make. SWLs can, however, be estimated using appropriate fan laws [1].
b) Prototype testing stage. With the type and make of fan now identified and a prototype constructed, SWLs can then be determined from tests at the manufacturer's works [2].
c) Pre-installation stage. With production models of the fan delivered to the shipyard for installation onboard, SWLs can be determined using sound pressure level (SPL) measurements [3] or sound intensity measurements [4].
d) Onboard. Once the fans are fitted onboard the submarine their SWLs would normally be found using sound intensity measurements. This would also apply to units on boats already in service.

3.3 Receiver points

The receiver points onboard a submarine are the positions at which calculated airborne noise levels, usually in terms of overall 'A' weighted SPLs, are compared with appropriate target levels. They are also the positions where SPL measurements are made during compartment surveys once the boat has been completed.

Receiver points are required in all compartments which are either continuously manned such as control rooms, bunkspaces, messes or recreational spaces, or where personnel have to enter from time to time, for example stores and machinery spaces. Such receiver points are chosen to allow representative estimates of noise levels to be determined for the entire compartment or solely for specific locations within the compartment such as Watchkeeper positions. The receiver point positions are identified once the submarine compartment layout has been finalised and the target levels set according to the purpose and use of each compartment.

3.4 Transmission paths

There are numerous transmission paths between each source and receiver point. For fans in particular, the following general types of path are present onboard submarines.

a) Direct airborne paths along the line of sight between a fan and receiver point combined with reverberant airborne paths due to diffraction and reflection of noise incident on compartment boundaries and objects, as shown in Figure 1. The SPLs at the receiver point and the SWLs of the fan can be related by functions based on the directivity of the source (D) the distance between the source and receiver (r) and the room constant of the compartment (R_C) as in equation 1 [5].

$$SPL = SWL + f(D, r, R_C) \qquad (1)$$

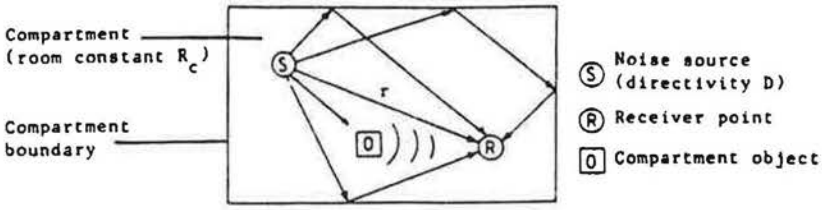


Fig.1. Direct & reverberant airborne paths within a compartment

b) Ventilation duct systems. Noise entering a ventilation supply or exhaust lead can be easily transmitted to many compartments throughout the boat. By subdividing each duct lead into its constituent elements (straight ducts, bends, transitions, etc.), aspects of noise including transmission along these elements, break in and break out noise via duct walls or openings (T) and flow noise (F) due to the movement of air in each duct element can be considered. For the example system in Figure 2, the equations required for its analysis would be of the form [1,6,7]:

$$SWL_3 = f\,(SPL_1,\ T_{13},\ SPL_2,\ T_{23},\ F_a,\ F_b) \tag{2}$$
$$SWL_4 = f\,(SPL_1,\ T_{14},\ SPL_2,\ T_{24},\ F_a,\ F_b) \tag{3}$$

The SWLs thus determined would then be used in Equation 1 to determine SPLs at the required receiver points.

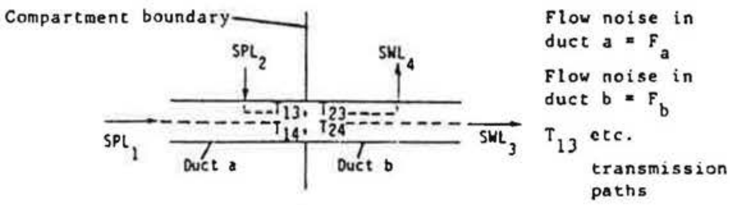


Fig.2. Sample ventilation duct model

c) Through common structure boundaries between, for example, a fan plenum and another compartment as shown in Figure 3. Noise transmitted via direct and flanking paths need to be considered and depend on the transmission losses (T) and areas (S) of the relevant compartment boundaries and the room constant (R_C) of the receiver compartment. Typical equations in the analysis of the example shown in Figure 3 would be [5,6]:

$$SPL_3 = SPL_1 + f(T_{13},\ S_1,\ R_C) \tag{4}$$
$$SPL_4 = SPL_2 + f(T_{24},\ S_2,\ S_4,\ R_C) \tag{5}$$

The SPLs incident on the boundaries of the source compartment would have first been calculated using Equation 1.

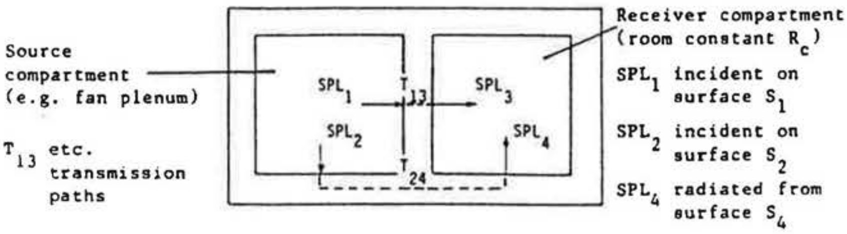


Fig.3. Direct & flanking transmission paths between compartments

4- CASE STUDY A

4.1 Design stage

The first case study concerns a submarine compartment containing a large number of machines. Consequently this compartment required several fans, each of the same type, to re-circulate and cool the air. The main consideration was that the combined airborne noise level due to the fans should not contribute significantly to the total compartment level.

At the design stage of the boat, SWLs for the fans and other machinery to be sited in this compartment were obtained from manufacturer's predictions, or from scaled data of other boats. The receiver point was chosen at the Watchkeeping location in the compartment and the transmission paths between the sources and this point established as being direct and reverberant airborne paths. The target level at the receiver point was 85 dBA.

A computer acoustic model of the compartment was formed using these SWLs. Information on the distance between the sources and the receiver point, the directivity of the sources and the room constant of the compartment was obtained from geometric data. SPLs were then calculated at the receiver point, and the resulting overall levels shown in Table 1. One can see from this table that the contribution of the fans was 5 dBA less than the total level, and the compartment target level was exceeded by 17 dBA. Following this prediction it was proposed that improved acoustic absorption insulant materials would be investigated as a first attempt to reduce levels. The acoustic model was re-run with different insulant options and results showed that the overall level in the compartment could be reduced by up to 4 dBA, as shown in Table 1, and the required insulation change was incorporated into the boat design.

4.2 Pre-installation stage

The source levels of fans and other machines in this acoustic model were updated at the pre-installation stage, when units were delivered on site for testing. It soon became clear that the SWL estimates of certain machines, for which only scaled data had been available at the design stage were pessimistic. The pre-installation tests on the fans for the compartment in question, however, showed levels that were greater than their source level estimates at the design stage. Running the acoustic model with the new SWLs, resulted in a prediction which indicated that the fans would be the largest contributor of noise in the compartment (98 dBA overall) as shown in Table 1.

Table 1. Overall sound pressure levels (compartment target level 85 dBA)

Prediction/Measurement	Contribution due to Fans (dBA)	Contribution due to all noise sources (dBA)
Design stage prediction	97	102
Design stage with improved insulation	93	98
Pre-installation stage prediction	98	98
Pre-installation stage with silencers	80	87
Measurement of fans onboard	81	87

At this point various possible acoustic treatments were investigated using the acoustic model by altering appropriate parameters. It was found that although some of the treatments proposed would reduce levels in the compartment, such as fitting extra insulation or erecting barriers between the fans and the receiver point, they would not be practical to install because of the advanced stage of boat build. However, the simplest solution and easiest to fit was to attach an appropriate inlet and outlet silencer to each fan knowing the available space envelope. As Table 1 shows, the contribution due to the fans was substantially reduced (by 18 dBA).

4.3 Build stage
Once the fans were fitted onboard with the silencers attached, SPLs were measured at the receiver point. From Table 1 one can see that the contribution of the fans agreed very well with the pre-installation prediction from the acoustic model and would only have a small effect on the total levels in the compartment. The total compartment level in this case was exceeded by 2 dBA and studies to reduce this level continue.

5- CASE STUDY B

5.1 Design stage
The second case study concerns a compartment with a low target level (60 dBA) linked to a noisy fan plenum, containing a main supply fan, via a ventilation supply lead. The receiver point was selected to be at the geometric centre of the compartment.

Once the manufacturer's estimate of SWLs became available, a computer acoustic model of the ventilation lead was created knowing its route and composition from design plans. The model predicted that levels in the receiver compartment would exceed its target level at the receiver point by 18 dBA as shown in Table 2. Fortunately, space envelopes in the otherwise cramped fan plenum were available for silencers to be fitted to the fan. Information on the appropriate sized silencers was incorporated into the acoustic model which was then re-run. Although the fitting of the silencers significantly reduced levels in the receiver compartment concerned to 63 dBA as shown in Table 2, its target level was still exceeded by 3 dBA.

Table 2. Overall sound pressure levels (Compartment target level 60 dBA)

Prediction/measurement	Levels in compartment (dBA)
Design stage prediction	78
Design stage silencers fitted to fans	63
Design stage silencers and double-skin ducts fitted	55
Pre-installation stage prediction	59
Measurement onboard	57

A closer analysis of the results from the model showed that although the duct route from the plenum to the compartment was fairly tortuous in order to fit into the submarine, flow noise generated by the various bends and constrictions in the duct lead was not a significant contributor of noise in this ventilation system. The main source was identified as the noise transmitted from the fan along the ventilation ducts.

Knowing that the acoustic absorption insulation in both the fan plenum and receiver compartment could not be improved, it was then decided that the acoustic model would be used to determine the effects of fitting double-skinned ducts. Such ducts are lined internally with foam/mineral fibre held in place with a perforated face plate. However, their cross-sectional area is increased accordingly to retain the open area of the duct for air flow as before. The acoustic model was re-run by altering the lining parameters of the ducts, with different proposed lengths of the double-skinned elements until SPLs in the compartment were predicted to be well within its target level as shown in Table 2.

5.2 Build stage

As the boat build progressed, it was realised that there would have to be a compromise between the ideal double-skin fit and what would be practical to install because of space constraints. Fortunately when the fan was tested at the pre-installation stage and its SWLs updated in the computer model, which was then re-run, the target level in the compartment was still met as Table 2 shows. This was confirmed when SPLs were measured in the receiver compartment once the fan had been installed, as shown in Table 2.

6- CASE STUDY C

6.1 Design stage

The final case study concerns a compartment sited immediately above a fan plenum and the prediction of noise levels transmitted via common structural boundaries. The target level for the receiver compartment in this assessment was 65 dBA and the receiver point located at the geometric centre of the compartment. A computer acoustic model of the two compartments was formed at the design stage once the initial SWLs of the fans became available and information regarding compartment structure, ventilation ducts, etc. became known. Results from this model in Table 3 show that the target level in the receiver compartment would be exceeded by 16 dBA, the main contributor of noise being via the ventilation ducts (78 dBA).

Table 3. Overall sound pressure levels (compartment target level 65 dBA)

Prediction/measurement	Contribution via ventilation ducts (dBA)	Contribution via structure (dBA)	Total (dBA)
Design stage prediction	78	77	81
Design stage silencers fitted to fans	75	74	78
Design stage silencers and double-skin ducts fitted	57	74	74
Design stage silencers, double-skin ducts and damping panels fitted	57	64	65
Pre-installation stage prediction	54	61	62
Measurement onboard	-	-	64

The first set of acoustic treatments investigated, concentrated on the fan itself and appropriate silencer attenuations were incorporated into the model which was re-run and the resulting level (78 dBA) is shown in Table 3. This indicated that further reductions in noise were necessary if the target level in the receiver compartment was to be achieved.

It was decided that the acoustic absorption material in the receiver or source compartments could not be improved so attention was then given to the transmission paths between the two compartments. As in the previous case study, the effect of double-skinned ventilation ducts was investigated and the appropriate results from the acoustic model are shown in Table 3. The table also indicates that the contribution via these ducts was reduced by such an extent (18 dBA) that the transmission paths via the common compartment structure between the fan plenum and receiver compartment would now be the dominant source of noise.

Although in this case it was not possible to change the thickness or the material of the intervening structure, space and access were available to apply damping panels to the deck separating the two compartments. Using the acoustic model, various types of damping panel were investigated and their effect on noise levels in the receiver compartment calculated. The damping material finally selected was a constrained layer composite consisting of a layer of rubber-like material faced with a sheet of steel. This particular material was used elsewhere on the boat and hence was readily available as a stock item thus reducing potential costs. The predicted level in the receiver compartment with this material in place was calculated to be 65 dBA as shown in Table 3, now attaining the target level of the receiver compartment.

6.2 Build stage

The silencers, double-skin ducts and damping panels were incorporated into the design of the boat. Predictions at the pre-installation stage showed that the receiver compartment target level would be met and this was confirmed with SPL measurements in the receiver compartment at the build stage as shown in Table 3.

7- CONCLUSIONS

This paper has shown through the case studies how computer acoustic models have been used to reduce airborne noise levels due to fans and their associated ventilation ducts in submarines. Such models allow individual or combinations of acoustic treatments to be analysed before boat construction takes place allowing those noise control measures which are required to be incorporated in the design of the boat.

REFERENCES

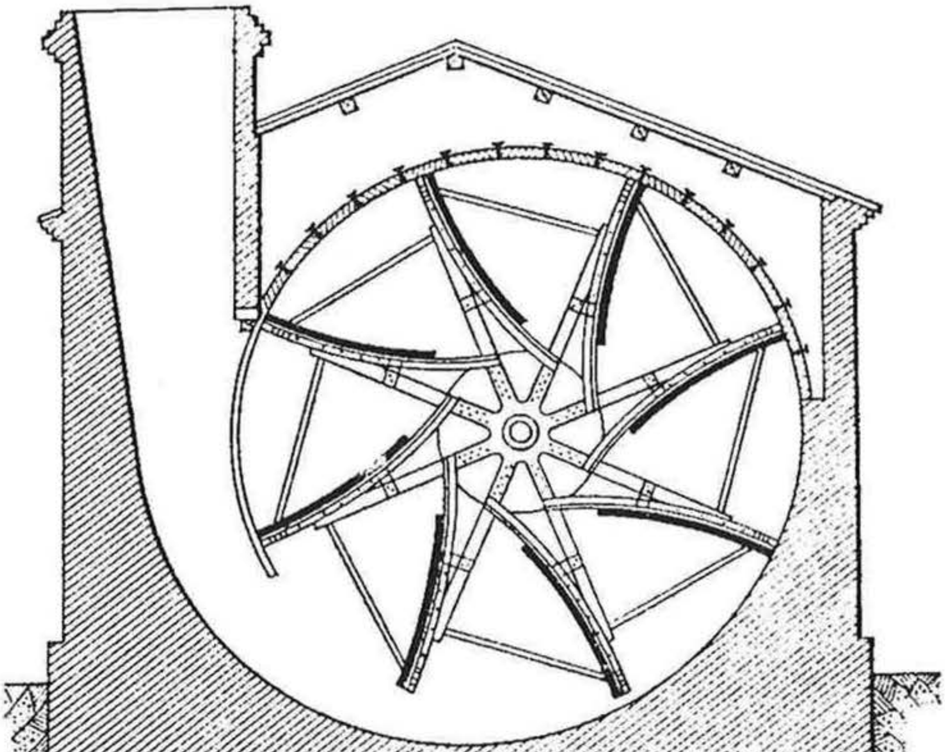
[1] Beranek, L.L., Noise Reduction, McGraw-Hill, USA, 1960
[2] BS 848 part 2 1985, Fans for General Purposes: Methods of Noise Testing
[3] BS 4196 parts 0-6 1981-86, Sound Power Levels of Noise Sources
[4] ISO DP 9614 Determination of the Sound Power Levels of Noise Sources Using Sound Intensity Measurements
[5] Beranek, L.L., Acoustics, AIOP, USA, 1986
[6] Beranek, L.L., Noise & Vibration Control, INCE, USA, 1988
[7] Sharland, I., Woods Practical Guide to Noise Control, Woods, UK, 1972

PUBLICATIONS CETIM

FAN NOISE

BRUIT DES VENTILATEURS

An International INCE Symposium



CETIM Senlis (France)
September 1-3, 1992
1-3 septembre 1992

SOCIÉTÉ FRANÇAISE D'ACOUSTIQUE

CETIM
CENTRE TECHNIQUE DES INDUSTRIES MECANIQUES